24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-0600
CYCLIC DEFORMATION AND FATIGUE OF 7050-T7451 ALUMINUM ALLOY

Karen Viviana Fabara Hernández
Cainã Bemfica de Barros
Fábio Comes de Castro
Jorge Luiz de Almeida Ferreira
Department of Mechanical Engineering, University of Brasilia, 70910-900 Brasilia, DF, Brazil
karenfabara@gmail.com, cainabemfica@gmail.com, fabiocastro@unb.br, jorge@unb.br

Abstract. *The cyclic stress-strain and fatigue behaviors of 7050-T7451 aluminum alloy are investigated in this work. Solid cylindrical specimens were subjected to strain-controlled uniaxial loading with strain ratio R_ε = -1 and 0.01 and strain amplitudes from 0.3% to 1.5%. For R_ε = -1, a small amount of cyclic softening was observed for strain amplitudes greater than 0.85%. For strain amplitudes less than 0.85%, insignificant cyclic hardening/softening was observed. For the fully reversed tests performed at strain amplitudes lower than 0.6%, the deviation in the ascending branches of the stabilized stress–plastic strain hysteresis loops indicates a non-Masing behavior. For R_ε = 0.01, small cyclic hardening was observed in the material for strain amplitudes greater than 0.5%, while insignificant cyclic hardening/softening was observed for strain amplitudes less than 0.5%. The tensile mean stress observed in the first loading cycle is relaxed when the strain amplitude is greater than 0.4%. No significant variation of the cyclic properties along the thickness of the alloy 7050 plate was observed in the range of fatigue lives investigated (10–10^5 cycles to failure). The Smith–Watson–Topper parameter can satisfactorily correlate the fatigue life of 7050-T7451 Al alloy under strain-controlled cycling with R_ε = -1 and R_ε = 0.01.*

Keywords: *7050-T7451 aluminum alloy, cyclic deformation, fatigue life*

1. INTRODUCTION

Aluminum (Al) alloys are widely used in the aeronautical industry due to its good combination of low density, high strength, resistance to corrosion, and fracture toughness. Other appealing features of Al alloys are their well-known performance characteristics, known fabrication costs, and design experience (Starke and Staley, 1996).

7050-T7451 aluminum alloy (AA7050-T7451) has been used in aircraft components such as fuselage frame, bulkhead, wing skin, and landing gear (Prasad and Wanhill, 2017). The low and high-cycle fatigue behavior, as well as cyclic deformation behavior, of AA7050-T7451 have been investigated in several studies (Carvalho and Voorwald, 2007; Deschapelles and Rice, 1996; Gao, 2011; Hu *et al.*, 1999; Knop *et al.*, 2000; Kourousis and Dafalias, 2013; Rusk *et al.*, 2006). Knop *et al.* (2000) highlighted the importance of taking the mean stress relaxation into account to properly predict the fatigue life of this alloy.

In this work, the cyclic stress-strain and fatigue behaviors of AA7050-T7451 under uniaxial loading are investigated. The experimental conditions included strain amplitudes from 0.3% to 1.5% and two strain ratios (R_ε = 0.01 and -1). The test data are used to evaluate the Smith–Watson–Topper fatigue criterion with respect to its capability to estimate the fatigue lives of the AA7050-T7451.

2. MATERIAL AND EXPERIMENTS

The material used in this study is a 7050-T7451 Al alloy received in the form of a rolled plate. The chemical composition of the material in weight percentage is 5.7–6.7 Zn, 0.06 Ti, 1.9–2.6 Mg, 2.0–2.6 Cu, 0.08–0.15 Zr, 0.15 Fe, 0.10 Mn, 0.04 Cr, 0.12 Si, and Al as balance. The Young's modulus of the material is 69.2 GPa, the 0.2% offset yield stress is 463 MPa, and the ultimate tensile strength is 524 MPa.

The microstructure of the AA7050-T7451 taken from the outer and inner layers of the plate is shown in Fig. 1. The axes L, S, and T in the figure refer to the rolling, short transverse (thickness), and long transverse directions, respectively. The microstructure of this alloy consisted of small recrystallized grains and unrecrystallized coarse grains elongated along the rolling direction. The dark spots are intermetallic particles of Al_7Cu_2Fe and Mg_2Si that are characteristic of AA7050-T7451. It is noted that the unrecrystallized regions are more pronounced in the inner layer of the plate. The average grain size along the thickness direction of the plate ranged from 2 µm to 5 µm.

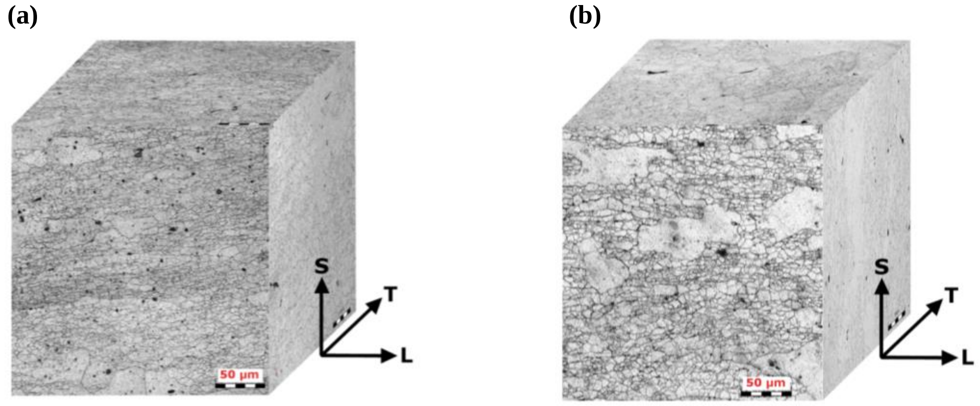

Figure 1. Microstructure of the AA7050-T7451 taken from the outer (a) and inner (b) layers of the rolled plate.

Solid cylindrical specimens (Fig. 2) with axes parallel to the longitudinal (rolling) direction of the plate were used in the fatigue experiments. To investigate the variation of the cyclic deformation and fatigue properties along the thickness of the plate, each specimen was labeled as shown in Fig. 3. The letter denotes the position within a layer, and the digit refers to the layer. The two outer layers of the plate were identified by the digits 1 and 7, and the inner layer of the plate by the digit 4.

The fatigue tests were carried out at room temperature on an MTS 810 servohydraulic machine equipped with the TestStar IIs digital controller. Strain-controlled experiments with a triangular waveform were conducted at various strain amplitudes (0.3% ~ 1.5%) and two strain ratios (R_ε = 0.01 and -1). An extensometer with a gage length of 25 mm and a range of +20% to -10% was used for the measurement of the strain. During each experiment, stress–strain hysteresis loops were recorded at predefined loading cycles. The specimens were tested until fracture into two parts or the appearance of a visible surface crack. The test data are summarized in Table 1, where the stress amplitude and mean stress were taken from a stress–strain hysteresis loop corresponding to approximately half of the number of cycles to failure.

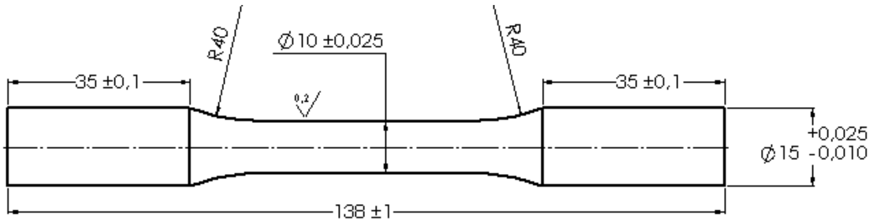

Figure 2. Specimen used in the fatigue experiments (dimensions in mm).

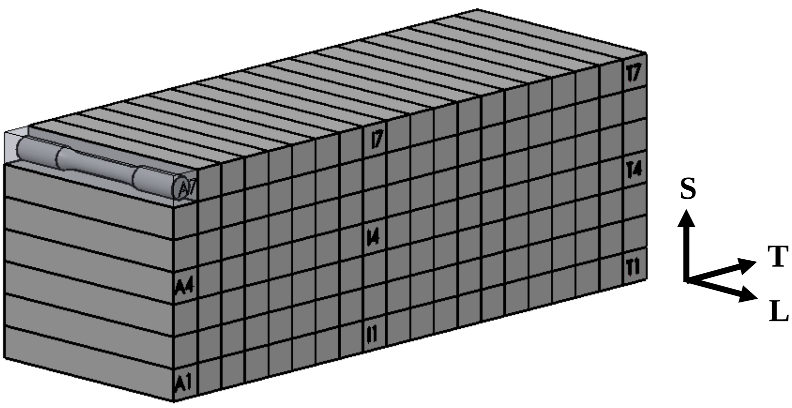

Figure 3. Division of the 7050-T7451 plate into specimens.

Table 1. Summary of the fatigue tests conducted on 7050-T7451 Al alloy.

Specimen ID	R_ε	f (Hz)	ε_a (%)	σ_a (MPa)	σ_m (MPa)	N_f (cycles)
L1	-1	0.25	1.50	449.0	-20.7	20
P7	-1	0.01	1.50	444.1	-12.3	45
M4	-1	0.01	1.50	443.7	-9.8	31
L4	-1	0.01	1.50	449.3	-13.9	30
J1	-1	0.04	1.10	419.2	-9.9	139
I7	-1	0.04	1.10	424.1	-11.9	89
K4	-1	0.04	1.10	431.9	-9.6	150
J4	-1	0.04	1.10	429.8	-13.1	62
F1	-1	0.25	0.85	403.8	-14.1	409
K7	-1	0.25	0.85	417.3	-20.9	374
F4	-1	0.25	0.85	406.8	-1.9	316
G4	-1	0.25	0.85	406.9	-15.0	295
F7	-1	0.25	0.60	372.6	-10.8	1159
G1	-1	0.25	0.50	340.6	-11.4	3120
D1	-1	0.25	0.50	340.0	-14.0	2523
I4	-1	0.25	0.50	343.9	-14.7	3292
H4	-1	0.25	0.50	344.9	8.9	3363
P4	-1	0.40	0.43	300.0	-2.3	11137
O4	0.01	0.01	1.50	448.9	-6.5	16
R4	0.01	0.01	1.50	447.8	-8.7	30
S1	0.01	0.01	1.10	424.6	-5.9	108
T1	0.01	0.01	1.10	428.6	-5.7	113
N4	0.01	0.01	0.75	382.8	16.9	392
S4	0.01	0.05	0.75	395.3	16.4	499
T7	0.01	0.20	0.50	338.6	57.9	1610
Q4	0.01	0.20	0.50	326.5	84.3	2211
F2	0.01	1.00	0.40	273.9	102.9	4500
Q5	0.01	1.00	0.30	204.3	160.7	7530

R_ε = strain ratio; f = frequency; ε_a = strain amplitude; σ_a = stress amplitude; σ_m = mean stress; N_f = number of cycles to failure.

3. RESULTS AND DISCUSSION

The variation of the stress amplitude with the number of loading cycles for the experiments conducted under fully reversed loading is shown in Fig. 4. The curves were obtained from test data corresponding to the specimens P7, K4, K7, P4, and H4. Similar cyclic deformation behavior was observed for the tests performed on the other specimens. The results shown in Fig. 4 indicate that the AA7050-T7451 under fully reversed loading exhibits cyclic softening for strain amplitudes greater than 0.85%. Also, the cyclic softening of this material never becomes stabilized. Such a behavior, however, is not very pronounced. For example, the stress amplitude during the test with ε_a = 0.85% varies from 445 MPa in the first loading cycle to approximately 414 MPa at the end of the test, a percentage reduction of only 7%. For strain amplitudes less than 0.85%, insignificant cyclic hardening/softening was observed. Compressive mean stresses within a range from -5 MPa to -20 MPa were identified in all experiments. After a few loading cycles, these compressive stresses remained constant until failure of the material.

The stress amplitude versus number of loading cycles for the experiments conducted at R_ε = 0.01 is presented in Fig. 5a. The curves refer to the test data obtained from specimens R4, T1, S4, T7, F2, and Q5. Small cyclic hardening was observed in the material for strain amplitudes greater than 0.5%. Indeed, the greatest percentage change between the stress amplitude at the beginning and at the end of such experiments was 13.3% and occurred when ε_a = 0.5%. For strain amplitudes less than 0.5%, insignificant cyclic hardening/softening was observed. It is noted that for the tests with strain amplitudes of 1.5% and 1.1%, the stress amplitude stabilizes after the tenth loading cycle. For the tests with strain amplitudes of 0.75% and 0.5%, the stabilization of the stress amplitude occurred after approximately 40 and 400 loading cycles, respectively. In all these loading conditions, the stress amplitude stabilized before half the number of cycles to failure. The mean stress versus number of loading cycles for the experiments conducted at R_ε = 0.01 is shown in Fig. 5b. The tensile mean stress observed in the first loading cycle is relaxed when the strain amplitude in greater than 0.4%. The rate of the mean stress relaxation is more pronounced during the first loading cycles and decreases as the number of loading cycles increases.

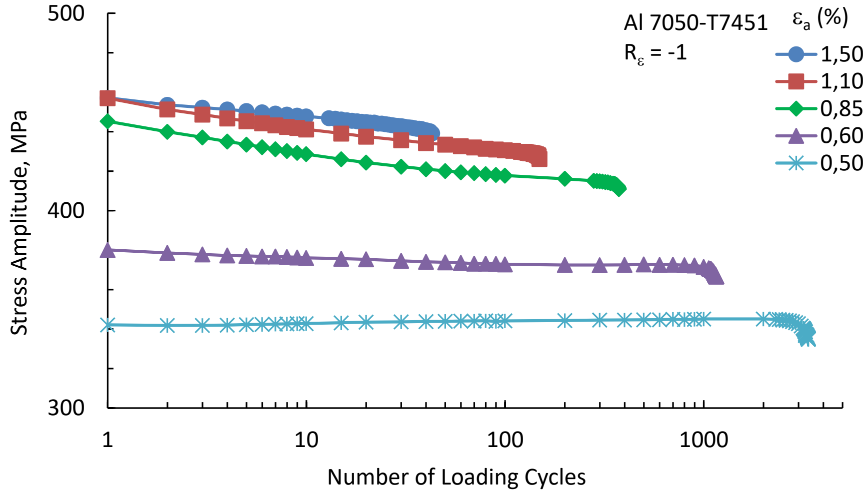

Figure 4. Stress amplitude versus number of loading cycles for fully reversed strain-controlled tests.

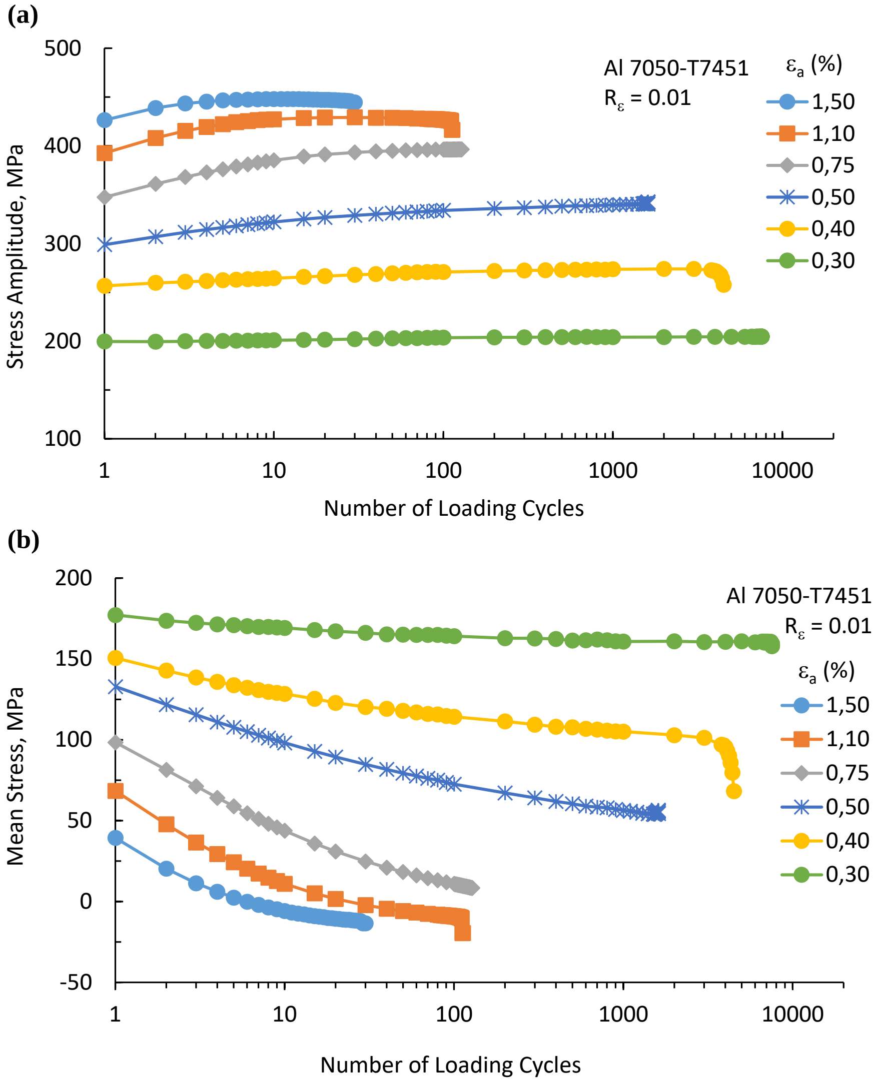

Figure 5. Stress amplitude (a) and mean stress (b) versus number of loading cycles for tests with $R_\varepsilon = 0.01$.

A material is said to exhibit *Masing behavior* when the shape of the stress-plastic strain hysteresis loops obtained at different strain amplitudes are geometrically similar (Masing, 1926; Ellyin, 1997; Jiang and Zhang, 2008). For this type of material, when the lower tips of the hysteresis loops are tied together the upper branches of the loops follow a unique curve. Figure 6 shows the stress-plastic strain hysteresis loops of AA7050-T7451 obtained from fully reversed strain-controlled tests conducted at strain amplitudes from 0.43% to 1.5%. The loops were taken at the number of cycles corresponding to half of the fatigue life of the specimen and were tied together at the lower tips. For strain amplitudes higher than 0.6%, the material exhibits a small deviation from the ideal Masing behavior. For strain amplitudes lower than 0.6%, the level of deviation in the ascending branches indicates a non-Masing behavior. It is noted that a similar behavior was observed in the study by Rusk *et al.* (2006) on an aluminum alloy with an identical designation.

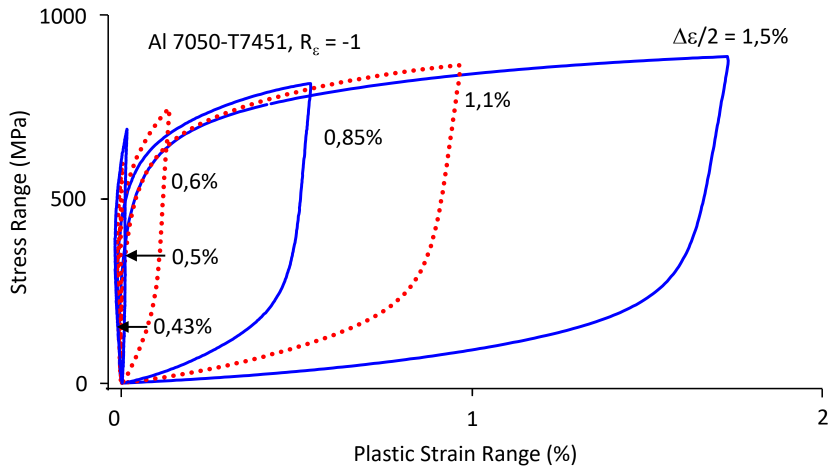

Figure 6. Stabilized stress–plastic strain hysteresis loops with the lower tips tied together.

Figure 7 presents the stabilized stress amplitude versus the stabilized plastic strain amplitude for AA7050-T7451, which were taken from half the number of cycles to failure. For the range of plastic strain amplitudes investigated, the test data show a good fit to the power law (Ramberg–Osgood) relationship. It is also noted that the test data for the material taken from the outer and inner layers of the rolled plate are quite similar, indicating that for the rolled plate investigated the cyclic deformation properties of the material does not vary significantly along the thickness direction.

Variation of the microstructure along the thickness direction of a rolled plate may affect the fatigue strength of the material. To investigate whether such an effect is important for the AA7050-T7451 rolled plate under study, the fatigue curves for the material taken from the outer and inner layers of the plate were obtained (Fig. 8). It is noted that the two fatigue curves are very similar, indicating that the variation of the strain-based fatigue properties along the thickness direction is insignificant for the range of fatigue lives investigated. However, it is important to emphasize that this conclusion may not hold for other AA7050-T7451 rolled plates and fatigue life regimes.

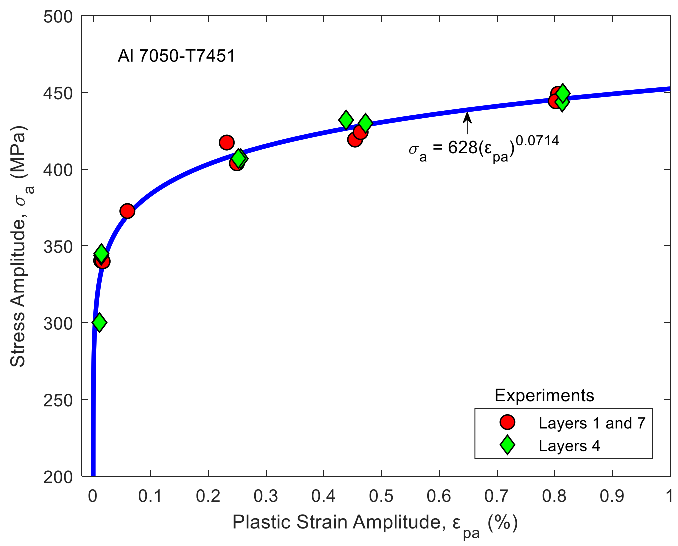

Figure 7. Stress amplitude versus plastic strain amplitude data for 7050-T7451 Al alloy taken from layers 1 and 7 (outer layers) and from layer 4 (inner layer) of the rolled plate.

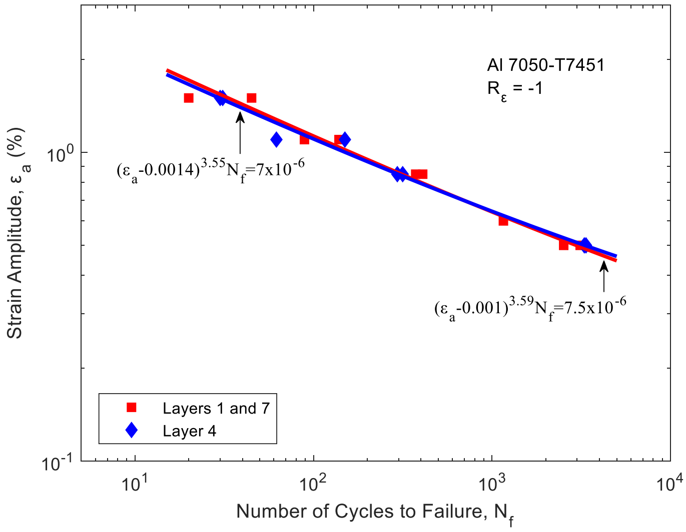

Figure 8. Fatigue curves of 7050-T7451 Al alloy taken from layers 1 and 7 (outer layers) and from layer 4 (inner layer) of the rolled plate.

The parameter developed by Smith, Watson, and Topper (1970) can provide reasonably accurate fatigue life estimates for aluminum alloys subjected to uniaxial loading with a superimposed mean stress (Dowling, 2009). The SWT parameter takes the following form:

$$FP = \varepsilon_a \sigma_{max} \tag{1}$$

where FP denotes "fatigue parameter", ε_a is the strain amplitude, and σ_{max} is the maximum stress in a loading cycle. The relationship between the SWT parameter and the number of cycles to failure, N_f, can be described by a three-parameter equation,

$$\left(\mathrm{FP} - \mathrm{FP}_0\right)^{\xi} N_f = C \tag{2}$$

where FP_0, ξ and C are constants obtained by best fitting the test data. The SWT parameter of each experiment was evaluated by using the stress–strain hysteresis loop at half fatigue life. Figure 8 shows the correlation between the SWT parameter and the fatigue life for the specimens tested. The two dashed lines are the factor-of-two boundaries. In addition to the strain-controlled fatigue data reported in this study, constant amplitude load-controlled test data of AA7050-T7451 obtained by Sá (2016) were also included in Fig. 8. All data points are within the factor-of-two lines, indicating that the SWT parameter correlates well the fatigue experiments under loading conditions investigated.

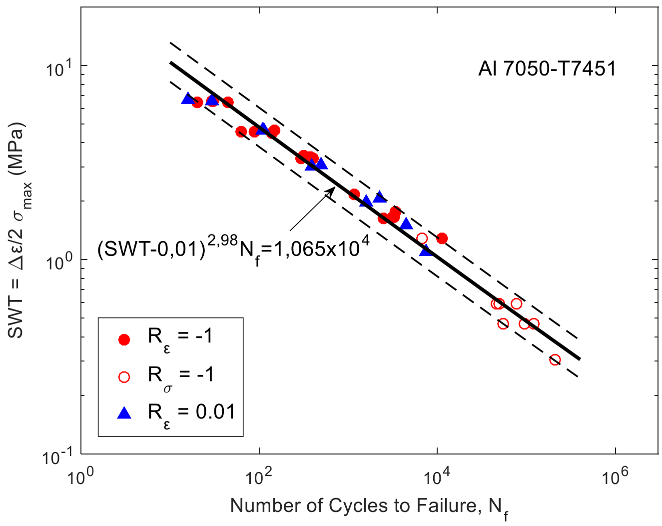

Figure 9. SWT parameter versus fatigue life.

4. CONCLUSIONS

Based on the strain-controlled fatigue tests conducted on AA7050-T7451 at two strain ratios (R_ε = -1 and 0.01), the following conclusions concerning the cyclic stress-strain and fatigue behaviors can be drawn:

1) For the tests performed at a strain ratio R_ε = -1 and strain amplitudes greater than 0.85%, the AA7050-T7451 exhibited during the whole test a small amount of cyclic softening. Insignificant cyclic hardening/softening was observed for specimens loaded at a strain amplitude less than 0.85%.
2) For the tests performed at a strain ratio R_ε = 0.01, the AA7050-T7451 exhibited a small amount of cyclic hardening for strain amplitudes greater than 0.5%. The stress amplitude stabilized before one-half of the fatigue life. Insignificant cyclic hardening was observed for specimens loaded at a strain amplitude less than 0.5%.
3) For the tests performed at a strain ratio R_ε = 0.01 and strain amplitudes greater than 0.4%, mean stress relaxation was observed, and its rate was more pronounced during the first loading cycles.
4) For the fully reversed tests performed at strain amplitudes higher than 0.6%, the material exhibited a small deviation from the ideal Masing behavior. For strain amplitudes lower than 0.6%, the deviation in the ascending branches of the stabilized stress–plastic strain hysteresis loops indicates a non-Masing behavior.
5) The variation of the strain-based fatigue properties along the thickness direction of the AA7050-T7451 rolled plate is insignificant for the range of fatigue lives studied. The variation of the cyclic deformation properties along the thickness direction was also observed to be insignificant.
6) For the tests performed at a strain ratio R_ε = 0.01 and strain amplitudes higher than 0.75%, the mean stress effect on the fatigue life was not significant. For strain amplitudes from 0.75% to 0.3%, fatigue life is reduced by up to a factor of 3.
7) The Smith–Watson–Topper parameter correlated the strain-controlled test data of AA7050-T7451 within a factor of 2 for all loading conditions investigated.

5. ACKNOWLEDGEMENTS

Fábio Castro and Cainã Bemfica acknowledge support from CNPq (contracts 308126/2016-5 and 131847/2017-1). Karen Hernández is grateful for the scholarship provided by CAPES.

6. REFERENCES

Carvalho A.L.M. and Voorwald H.J.C., 2007. "Influence of shot peening and hard chromium electroplating on the fatigue strength of 7050-T7451 aluminum alloy". *International Journal of Fatigue*, Vol. 29, n. 7, p. 1282-1291.

Deschapelles J.B. and Rice R.C., 1998. "Improved fatigue resistance of 7050 thick plate aluminum through minimization of porosity". In *Effects of product quality and design criteria on structural integrity*, ASTM International.

Dowling N.E., 2009. "Mean stress effects in strain–life fatigue". *Fatigue & Fracture of Engineering Materials & Structures*, Vol. 32, p. 1004-1019.

Ellyin, F., 1997. *Fatigue damage, crack growth and life prediction*. Published by Chapman and Hall, United Kingdom.

Gao Y.K., 2011. "Improvement of fatigue property in 7050–T7451 aluminum alloy by laser peening and shot peening." *Materials Science and Engineering A,* Vol. 528, n. 10, p. 3823-3828.

Hu, W., Wang, C. H. and Barter, S., 1999. "Analysis of cyclic mean stress relaxation and strain ratchetting behaviour of aluminium 7050". DSTO-RR-0153, Aeronautical and Maritime Research Laboratory.

Jiang Y. and Zhang J., 2008. "Benchmark experiments and characteristic cyclic plasticity deformation". *International Journal of Plasticity*, Vol. 24, n. 9, p. 1481-1515.

Knop, M., Jones, R., Molent, L. and Wang, C., 2000. "On the Glinka and Neuber methods for calculating notch tip strains under cyclic load spectra". *International Journal of Fatigue*, Vol. 22, n. 9, p. 743-755.

Kourousis K.I. and Dafalias Y.F., 2013. "Constitutive modeling of aluminum alloy 7050 cyclic mean stress relaxation and ratcheting". *Mechanics Research Communications* Vol. 53, p. 53-56.

Masing, G., 1926. "Eigenspannungen und verfestigung beim messing". In *Proceedings of the 2nd International Congress of Applied Mechanics*, Vol. 100, p. 332-335.

Prasad, N.E. and Wanhill, R.J.H. (Editors), 2017. *Aerospace materials and material technologies*. Springer.

Rusk, D. T., Taylor, R. E. and Hoffman, P. C., 2006. "Testing of 7050-T7451 aluminum strain-life coupons for a probabilistic strain-life curve". Naval Air Warfare Center Aircraft div Patuxent River MD.

Sá, M.V.C., 2016. "Previsão de vida à fadiga em componentes entalhados em condições multiaxias utilizando a teoria da distância crítica na liga Al 7050-T7451". *Internal Report (in Portuguese)*. University of Brasilia, Brasilia.

Smith R.N., Watson P. and Topper T.H., 1970. "A stress-strain function for the fatigue of metals". *Journal of Materials* Vol. 5, n. 4, p. 767–778.

Starke E.A. and Staley J.T., 1996. "Application of modern aluminum alloys to aircraft". *Progress in Aerospace Sciences,* Vol. 32, n. 2-3, p. 131-172.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.